DESIGN OF THE CASSINI TOUR TRAJECTORY IN THE SATURNIAN SYSTEM

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The Cassini mission to Saturn employs a Saturn orbiter and a Titan probe to conduct an intensive investigation of the Saturnian system. The Cassini orbiter flies series of orbits incorporating flybys of the Saturnian sate.llitcs called the "satellite tour". During the tour, the gravitational fields of the satellites are used to modify and control the orbit, targeting from one satellite flyby to the next. The tour trajectory must also be designed to maximize opportunites for science observations, subject 10 mission-imposed constraints. 'l"our design studies have been conducted for Cassini 10 identify trades and strategies for achieving these sometimes conflicting goals. Concepts, strategies, anti techniques previously developed for the Galileo mission to Jupiter have been modified, anti new ones have been developed, to meet the requirements of the Cassini mission.

1. INTRODUCTION

The Cassini mission will be the first 10 visit the Saturn ian system in the more than two decades which will have elapsed since the. Voyager flybys in 1980 and 1981. Cassini will conduct an intensive investigation of Saturn, its rings, satellites, and magnetosphere for four years,

After its insertion into orbit about Saturn, the Cassini orbiter travels in a series of highly elliptical orbits about Saturn. This series of orbits is referred teas the "sate.llitc tour". A large portion of the mission's scientific objectives arc accomplished during (his portion of the mission, and the design of the tour trajectory is an important factor in achieving these objectives.

The tour contains approximately 35-40 close, "targeted" flybys of Saturnian satellites. A targeted flyby is one where the orbiter's trajectory has been designed to pass through a specified aimpoint (latitude, longitude, and altitude) at the closcsI approach, in order to usc the satellite's gravitational in fluence to produce a desired change in the trajectory. Targeted flybys are capable of making large changes in the orbiter's trajectory. A single targeted flyby can change the orbiter's Salum-relative velocity by hundreds of m/s. For comparison, the total AV available from the. orbiter's thrusters is about 500" m/s for the entire tour containing 35-40 encounters.

Each targeted flyby is used to target the orbiter 10 the next flyby. The abundance. of aimpoints at each satellite encounter makes possible a large number of tours, each of which may satisfy many of the scientific objectives in different ways. While it is relatively easy to design a tour to satisfy any single scientific requirement, it is difficult to design a single tour which completely fulfills all the requirements, because the trajectories needed to satisfy different scientific requirements are often dissimilar. The scientific objectives of the tour arc discussed in the introduction to this volume.

Tour design involves maximizing science return in competing scientific areas while. satisfying mission-imposed constraints. This is a complex task, as experience in designing satellite tours for the. Galileo mission to Jupiter showed (Wolf and Byrnes, 1993; D'Amario, Bright, and Wolf, 1992). Tour design studies have been conducted for Cassini building on the wealth of experience gained from Galileo. Trades between areas of scientific interest and methods of meeting constraints are examined here, and a sample tour is presented.

The Cassini spacecraft carries the Huygens atmospheric probe, which is released into the atmosphere of Titan. Upon arrival at Saturn, a maneuver is performed to siow the spacecraft and insert it into orbit about Saturn. Near the first apoapsis, another maneuver is performed which simultaneously raises the periapsis distance from Saturn and targets the spacecraft to the desired flyby aimpoint at Titan. Closer 10 Titan, the spacecraft (both orbiter and probe) is maneuvered onto a Titan impact trajectory. The orbiter then separates from the probe and performs a maneuver which deflects it away from impact onto the desired flyby trajectory. The probe continues on the impact trajectory, enters the atmosphere, and relays its data through the orbiter to Earth as the orbiter flies overhead. The probe mission is described in detail in Section 4. The orbiter continues on along the tour trajectory.

2. *TOUR DESIGN CONCEPTS*

During the tour, the gravitational fields of' satellites are used to make large alterations in the trajectory. The concept of gravitational assist has been extensively discussed previously (Uphoff *et al*, 1979; Minovitch, 1972; Niehoff, 1971) and employed in previous missions. In brief, a satellite flyby can change the direction, but not the. magnitude, of the orbiter's velocity relative to tbc satellite. This change in the direction of the satellite-relative velocity vector can change both the direction and the magnitude of the o]-biter's velocity vector relative to the central body (Saturn, in the case of the Cassini tour). Since gravitational assist is fundamental 10 tour design, it is explored in greater detail in this section.

In the vicinity of a satellite, the orbiter's trajectory approximates a satellite-ccnkwcd hyperbola. The satellite-relative velocity vector along the incoming asymptote of this hyperbola (called $\mathbf{V}_\infty$) is compute.d by subtracting the satellite's Saturn-centered velocity from the orbiter's, The orbiter approaches from "infinity" (i. e., a point far enough from the satellite to be outside its gravitational influence) along the incoming asymptote of the hyperbola with a satellite-relative speed of V_∞. It gathers speed as it nears the satellite, attaining its greatest satellite-relative speed at closest approach. Its satellite-rc.lative speed decreases to V_∞ as it departs along the outgoing asymptote. The angle between its incoming and outgoing asymptotes is referred to as the bending angle. The flyby altitude necessary 10 achieve a given bending angle is determined by the following equation:

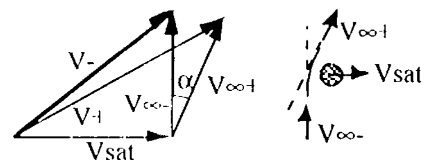
$$\sin(\alpha/2) = 1/(1 + r_p V_\infty^2 / \mathrm{p}) \qquad (1)$$

where α is the bending angle, r_p is the closest approach]-adios, V_∞ is the sate.1 lite-relative speed at infinity along either asymptote, and μ is the satellite's mass. The orbiter's Saturn-relative velocity after the flyby is then obtained by adding the satellite's Saturn-centered velocity to the orbiter's post-flyby $\mathbf{V}_\infty$.

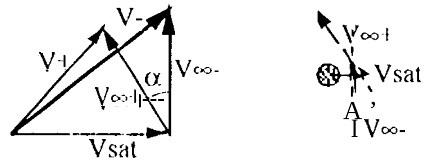
The vector diagram shown in Figure 1 illustrates how a change in direction of the V_∞ vector can result in a change in both magnitude and direction of the orbiter's Saturn-centered velocity. In order to avoid violating the principle of conservation of energy, the satellite's Saturn-relative speed decreases if the flyby increases the orbiter's Saturn-relative speed (and vice versa). Bc.cause the satellite is so much more massive than the orbiter, the change in the satellite's speed is insignificant.

According to the above equation, the more massive the sale. ililc., tbc greater the bending angle. The only satellite of Saturn which is massive enough to use for orbit control during a tour is Titan. The masses of the others arc. so small that even close flybys (within several hundred km) change the orbiter's orbit only slightly. Consequently, Cassini tours consist mostly of Titan flybys. This places restrictions on how the tout must be designed. Each Titan flyby must place the orbiter on a trajectory which leads back to Titan. The orbiter cannot be targeted to a flyby of a satellite other than Titan unless the flyby lies almost along a return path to Titan. Otherwise, since the gravitational influence of the other satellites is so small, the orbiter will not be able to return to Titan, and the tour cannot continue.

Energy Increasing ("pump up"):



Energy Decreasing ("pump down"):



$V-$, $V+$ = orbiter 's velocity vector relative to Saturn (pre- and post-flyby)

Vsat = Titan's velocity vector relative to Saturn

$V_{\infty-}$, $V_{\infty+}$ = orbiter 's velocity vector relative to Titan along an asymptote (pre- and post-flyby)

Fig. 1 Vector diagram illustrating tile usc of gravitational assist to achieve "orbit pumping".

2.1 Pumping and cranking

Flybys can be used 10 achieve *orbit pumping*, that is, changing the orbital pet iod with respect to Saturn, or *orbit cranking*, changing tile orbit without changing its period. Increasing the period (referred to as "pumping up") with respect to the central body is accomplished by flying behind a satellite's trailing edge. Decreasing the period ("pumping down") involves frying ahead of its leading edge. Figure 1 illustrates orbit pumping.

Flybys which change the. orbital period aiso rotate the line of apsides (the line connecting the periapsis and apoapsis points) and change the distance of the periapse from Saturn. The (iii-cction in which the iinc of apsides is rotated depends on whether the period is increased or decreased, and on whether the. flyby occurs before Saturn-relative periapse ("inbound") or afterwards ("outbound"). Figure 2 shows that an outbound, period-reducing flyby (from orbit A to orbit B) rotates the line of apsides clockwise, and an outbound period-increasing flyby (from B to A) rotates the line counterclockwise. Rules for orbit rotation are listed in Table 1.

Orbit cranking is illustrated in Figure 3. As the figure shows, in pure orbit cranking the pre- and pm-flyby velocity magnitudes relative to Saturn arc the. same., as arc 'tile pre- and post-flyby velocity magnitudes relative 10 the satellite. Since the Saturn-centered speeds arc the same before anti after the flyby, the pre- and post-flyby orbital periods arc aiso the same.

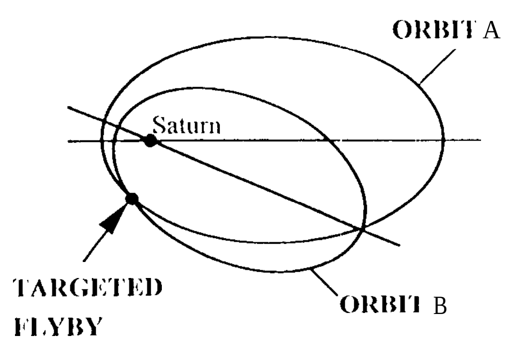
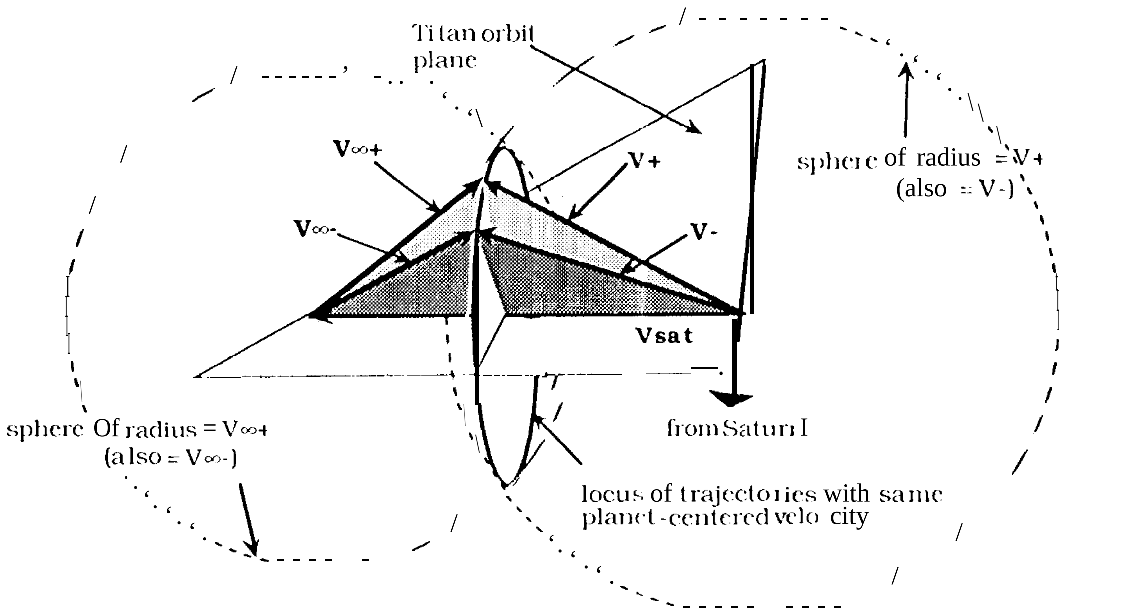


Fig. 2. Rotation of line of apsides.

Table 1: Orbit Rotation Rules

Flyby location	Energy (period) increasing flyby	Energy (period) decreasing flyby
Inbound (pre-periapse)	Clockwise	Counterclockwise
Outbound (post-periapse)	Counterclockwise	Clockwise

Note: Clockwise rotation is in the direction from the initial orbit orientation (near the dawn terminator of Saturn) toward the anti-sun direction.



V-, V+	=	orbiter's velocity vector relative to Saturn (pre- and post-flyby)
Vsat		Titan's velocity vector relative to Saturn
V∞-, V∞+	=	orbiter's velocity vector relative to Titan along an asymptote (pre- and post-flyby)

Fig. 3. Vector diagram illustrating the use of gravitational assist to achieve "orbit cranking".

The figure shows that in pure cranking, the locus of all possible $\mathbf{V}_\infty$ vectors after a flyby lie on a sphere centered at the heart of $\mathbf{V}_{sat}$, and the locus of all possible V vectors lie on a sphere centered at tile tail of $\mathbf{V}_{sat}$. Using a series of pure-cranking flybys, the heads of the V_∞ and V vectors can be placed anywhere on tile circle of intersection of these two spheres. (A single flyby can move these vectors over oniy a small arc in the circle, due to bending angle limitations.)

If the plane of the pre-flyby Saturn-centered orbit is near Saturn's equator, cranking changes the orbital inclination. If the pre-flyby orbital plane is significantly inclined to the equator, cranking mostly changes the periapse and apoapse radii, while keeping the semimajor axis length constant. (Since the period of an elliptical orbit depends on the length of the ellipse's semimajor axis, the semimajor axis length must be kept constant in order to keep period constant.)

If the orbital period (i.e., Va) and V_∞ are held constant, pure orbit cranking can raise the inclination only to a maximum value which is described by tile following relationship, taken from Uphoff *et al*:

$$i_{max} = \arccos [(V_{sat}^2 + V_-^2 - V_\infty^2) / 2 V_{sat} V_-] \quad (2)$$

where i_{max} is tile maximum inclination, V_S is the magnitude of Titan's velocity, V. is the magnitude of the orbiter's Saturn centered velocity before the flyby, and V_∞ is the hyperbolic excess speed (the magnitude of the V_∞ vector) with respect to Titan. As the inclination gets higher, pure cranking causes greater changes in periapse/apoapse radii, and a smaller change in inclination. The theoretical maximum inclination is approached asymptotically. The first few flybys wise inclination most of tile way, and the last few degrees of inclination require several flybys

" If V_∞ alone is held constant, the maximum inclination achievable with pure cranking changes with orbital period, because varying period al constant V_∞ cause s V. to change. The lower the period, the higher is the maximum inclination.

11 the inclination 10 Saturn's equator is high, pure pumping changes the inclination significantly in addition to changing the period. Reducing the period inc[-cases the inclination; increasing the period reduces the inclination.

The gravitational assist obtained from a single satellite flyby may consist of pure pumping, pore cranking, or pumping and cranking components. The total bending angle (obtained from both pumping and cranking components) must not exceed the value obtained from the bending equation at the minimum allowed flyby altitude.

Orbit pumping and cranking are discussed in detail in Uphoff, *et al.*

2.2 *Orbit orientation*

The angle measured clockwise at Saturn from the Saturn-sun line to the apoapse, referred to as the "orbit orientation", is an important consideration for magnetospheric observations. The time available for observations of Saturn's lit side decreases as the orbit rotates toward the anti-sun direction. Arrival conditions at Saturn fix the initial orientation at about 90 deg. Due to the motion of Saturn around the sun, the orbit orientation increases with time, at a rate of about I deg./month. Over the 4-year nominal duration of the tour, the total amount of clockwise drift in orbit orientation is about 48 deg. Period-changing targeted flybys which rotate the line of apsides may be used to add to or subtract from this drift in orbit orientation. Figure 4, referred to as a "petal plot" because of the resemblance of the orbits to tbc petals of a flower, shows how the orbit rotates from the initial orientation to near the anti-sun direction in tbc sample tour. in the coordinate system used in this figure, the direction to the sun is fixed,

2.3 *Transfer orbits of 180 and 360 deg.*

in general, tbc plane of the transfer orbit between any two flybys is formed by the position vectors of the flybys from Saturn. If the angle between the position vectors is other than I 80 or 360 deg. (as is usually the case), the orbital plane formed by these two vector-s is unique, and tics close to Titan's orbital plane, which is close to Saturn's equator. If the transfer angle is either 360 deg. (i.e., the two flybys occur at the same place), or I 80 deg., an infinite. number of orbital planes connect the flybys. In this case, the plane of the transfer orbit can be inclined significantly to the planet'$ equator. Any inclination can be chosen for the transfer orbit, as long as sufficient bending is available from the flyby to get to that inclination.

It can also be said that if a spacecraft's orbital plane is significantly inclined to the equator, the transfer angle between any two flybys forming this orbital plane must be nearly 180 or 360 deg. '

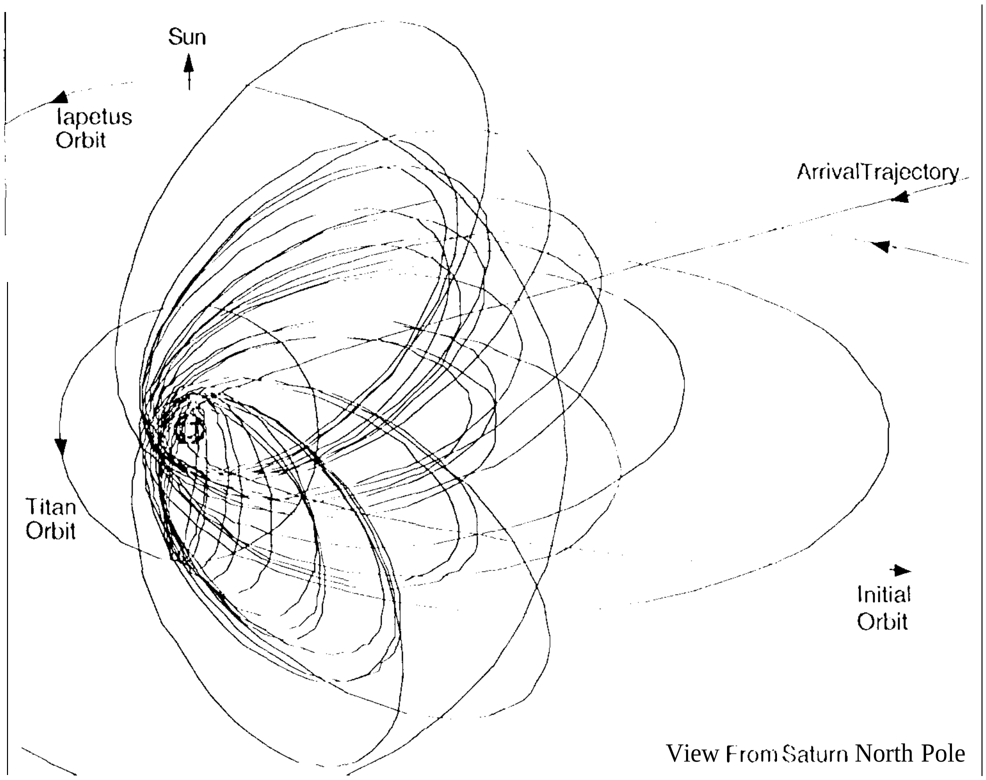


Fig. 4. "Petal plot" of sample Cassini tour, viewed from Saturn's north pole. Orbits are plotted in a rotating coordinate system, with the Saturn-Sun direction fixed at the top of the page.

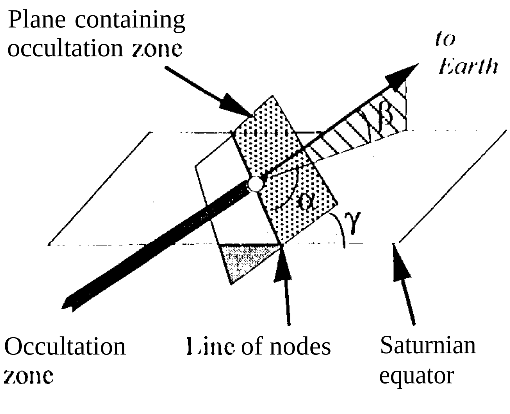
. 2.4 *Inclination required for occultations of Saturn*

Saturn's equatorial plane is tilted 28 deg. to the ecliptic, The declination of Earth with respect 10 the Saturnian equator is zero only at two points in Saturn's orbit about the sun. '1'0 an Ilar[tl-based observer, the rings appear edge-on only at those two points. As it happens, the rings never appear edge-on during the tour. At the time of the Cassini spacecraft's arrival, the declination of Earth is -25 deg; four years later, it is -7 deg. Unless the decl ination of Earth is near zero, a spacecraft orbiting in Saturn's equator-ial plane dots not pass behind Saturn as viewed from Earth. In this case, occultations of Earth by Saturn as viewed from the orbiter can be achieved only by inclining the orbital plane 10 the equator. Targeted satellite flybys arc. needed 10 raise the inclination to the required value.

The value of the inclination required to achieve an occultation is a function of the equatorial tilt viewed from Earth, and the angle between the Saturn-sun line and the line of nodes (the line connecting the points where the orbiter crosses Saturn's equator). An illustration of this relationship is provide.cl in Figure 5. For a given equatorial tilt angle (i.e., at any point in Saturn's or it), the inclination required 10 obtain an occultation is minimized when the line of nodes is perpendicular to the Saturn-Earth line. Targeted satellite flybys arc situated nearly along the line of nodes. It is desirable, therefore, to locate inclination-raising flybys nearly perpendicular to the Earth line in order to minimize the inclination (and therefore, the number of flybys) required 10 obtain occultations.

2.5 Nontargeted flybys

If the closest approach point during a flyby is far from the satellite, or if the satellite is small, the



α = angle between line of nodes anti Ear [b line., projected on Saturnian equator

β = declination of Earth

γ = Inclination of plane containing occultation zone (orbital plane require.d to achieve occultation)

Fig. 5. Orbital geometry require.ct 10 achieve occultations of Earth by Saturn, as viewed from the orbiter. The inclination required to achieve such an occultation is minimized when the line of nodes is perpendicular to the Earth line..

gravitational effect of the flyby can be small enough that the aimpoint at the flyby need not be tightly controlled. Such flybys arc called "nontargeted". Flybys of Titan at distances greater than 25,000 km and flybys of satellites other than Titan at distances of greater than a few thousand km arc considered nontargeted flybys. Flybys of satellites other than Titan at distances up to a few thousand km must be treated as "tar geted" flybys to achieve scientific objectives, even though their gravitation] influence is small. Opportunities to achieve nontargeted flybys of smaller satellites occur frequently during tbc tour. These arc important for global imaging.

3. CONSTRAINTS

Tour design is constrained by many factors, some of which arc duc to the laws of orbital mechanics, and others of which are unrelated to (hose physical laws. Constraints arc imposed duc to tbc limits of hardware capabilities, instrument reliability, operational necessities, and budgetary concerns.

The arrival conditions at Saturn arc fixed by the interplanetary trajectory. The orbiter arrives at Saturn on 1 July, 2004. This date. was chosen for reasons of performance and because it permits a flyby of Phoebe on approach 10 Saturn, The spacecraft arrives from an orbit near the ecliptic plane, at an inclination of approximately 17 deg. to Saturn's equator. A propulsive maneuver is executed to insert the orbiter into orbit about the planet.

The tour's maximum duration has been set at four years for budgetary reasons. The nominal tour must be finished four years after insertion into orbit about Saturn

The orbiter must avoid crossing tbc ring plane within regions in the ring system in which impacts with particles arc likely. Ring plane crossings must occur at 2.7 Saturn radii (RS) or greater, for this reason.

Titan's atmosphere imposes a minimum flyby altitude constraint, Thermal ancl attitude control considerations duc to atmospheric drag arc the limiting factors. For the sample tour presented here, the lover altitude limit is assumed to bc 950 km.

The time interval between targeted flybys must be large enough to allow detailed operational preparation for the next encounter to occur. For the Galileo mission to Jupiter, this interval was set at 35 days. At this early stage in the Cassini project, all the details of operational preparation between encounters have not yet been decided upon. However, the advanced design of [Ire. Cassini ground system is expected to allow the minimum time between flybys to be as low as 16 days for at least a few orbits, and probably in the range of 19-2(J days for the rest of the tour.

Only a limited amount of propellant is available for tour operations. Propellant is used only to provide small adjustments to the trajectory necessary to navigate the orbiter, to turn the orbiter in order to obtain scientific observations or to communicate with Earth.

4. METHODS AND SOFTWARE

While the basic concepts used in tour design arc straightforward, the process of arriving al an estimate Of the 10ur trajectory preci SC enough to be considered flyable is heavily dependent on software and modern high-speed computing hardware. The design of a tour proceeds through three stages: initial design, optimization, and integration. The division of the process into these stages is a consequence of the tradeoff between the initial need for fast (but not necessarily precise) trajectory computations for study purposes, and the eventual necessity of producing a precise estimate of the final trajectory chosen.

The initial design is done using highly interactive software which enables the user to evaluate various trajectory options quickly. The tour is designed onc flyby at a time. At each flyby, the user chooses from a set of aimpoints presented by the program, each of which leads to a different subsequent flyby. At any point in the tour, if the user is dissatisfied with the, trajectory, hc or shc can return to any previous flyby and c}1oosc a different set of encounters after (hat flyby. In this fashion, the user can quickly evaluate which trajectory options best achieve the scientific objectives of the tour without violating the mission constraints.

The result of the initial design stage is a mathematical representation of each orbit in the tour as an ellipse about Saturn (and, when near a flyby, a hyperbola about the flyby satellite). "1'hild-body effects such as the oblateness of Saturn and the gravitational effect of the Sun, which must be modelled in order to successfully fly the trajectory, arc so far unaccounted for. These arc modelled in the next stage, during which the trajectory is optimized. The initial representation of the trajectory is used as a "first guess," used to start the optimization process in a separate program. Trajectories arc propagated between breakpoints in the tour from initial position and velocity estimates using an algorithm which includes third-body effects. Velocity discontinuities (represented in the trajectory as deterministic propulsive maneuvers) initially appear at the breakpoints. The optimiz.alien program varies the flyby times and aimpoints to minimize the weighted sum of the AV's, in the process usually driving most of the maneuvers 10 zero. The estimate of total deterministic AV resulting from this process is almost always less than that obtained from the initial design stage.

The output of the optimization program is then passed to a precision integration program in the form of position and velocity estimates at various points in the tour. A search is performed between cacb set of breakpoints to find the precise velocity at (hc starting point of each leg needed to reach the required position al the cad of the leg. Because of the accuracy of the trajectory modelling incorporated in the optimization program, differences between the results obtained in the optimization and integration programs arc small. The result of the integration process can be used as a nominal estimate of a flyable trajectory.

5. RESULTS

A brief summary of a sample tour, showing the sequence of encounters anti some objectives accomplished at each encounter, is presented in'1'able 2. in this [able, encounters arc numbered according to the orbit on which they occur (e.g., Titan 3 occurs on orbit 3). Nontargeted encounters are designated with an "N" (e.g., Enceladus 3N). Since encounters do not occur on each orbit, they arc not numbered in consecutive order. For example, the Titan flyby on the ninth orbit is numbered Titan 9, but there is no fly by on the tenth orbit, so the next flyby is Titan 11, occurring on the eleventh orbit. According to the orbit numbering convention used, the orbit number changes at apoapsis, with orbit 1 beginning at the periapsis raise maneuver.

This tour contains 38 close satellite flybys and 63 orbits. Of these flybys, 33 arc of 'f 'itan and 5 of other satellites. Onc targeted flyby each of Enceladus, Tethys, Dione, Rhea, and Iapetus occurs. The first three Titan flybys reduce period anti inclination. The orbiter's inclination is reduced to near zero with respect to Saturn' s equator only after the third flyby; therefore, these three flybys must all take place at the same place in Titan's orbit. These period-reducing flybys were designed to be inbound, rather than outbound, in order to accomplish the additional goal of rotating the line of apsides courrter-clockwise. This moves the apoapse toward the sun line in order to provide time for observations of Saturn's atmosphere. After the inclination has been reduced to near Saturn's equator, a series of alternating outbound/period-increasing anti inbound/ period-reducing flybys is used to rotate the orbit further toward the sun line, the last of which is the Titan 9 flyby. Targeted flybys of Rhea (on orbit 4) and Dione (orbit '/) arc achieved along the way.

After the Titan 9 flyby, the.orbital geometry is such that for a Titan outbound encounter, the line of nodes is approximately perpendicular to the Earth line. This geometry minimizes the inclination required to achieve an occultation of Saturn. The Titan 11 and 12 flybys, both outbound, are designed (o increase inclination in order to take advantage of Ibis opportunity. The timing of these two flybys was chosen judiciously so as to arrange an encounter with Iapetus while raising inclination. Since Iapetus' orbit is inclined nearly 15 deg. to Saturn's equator, it is necessary to raise inclination to at least 15 deg. in order to achieve an Iapetus flyby. The increased inclination achieved after Titan 12 allows a targeted flyby of Iapetus on the thirteenth orbit. The Titan 13 flyby increases inclination further to just over 20 deg., the value required to obtain equatorial occultations of Saturn and the rings at this point in the tour. No sate.llilc flybys occur during the next three orbits, in order to allow inclination to remain at this value long enough to achieve three near-equatorial occultations. These occultations arc illustrated as they appear to an Earth-based viewer in Figure 6. After these llavc.been achieved, two Titan flybys (Titan 16 and 17) arc required to lower the inclination to near the equator.

J'able 2: Summary of Sample Tour

Encounter	Date/Time yymmdd.hhmmss	Alt. (km)	Lat. (deg)	W.Lon. (deg)	Post-flyby inclination to Saturn equator (deg.)	Comments
Titan I	041127 1S0529	1500	61	105.1	10.5	Reduce period, inclination
Titan 2	050215082823	1250	61.9	87.9	2.1	
Titan 3	050404042747	2397	17.1	73.2	0.5	Rotate orbit counterclockwise
Rhea 4	0s0503055408	999	-73.1	270.5	0.S6	
Dione 4N	050503120712	I 3377	-11	290.6	0.5	Imaging (nontargeted flyby)
Titan 5	050602182838	4408	1.4	286.9	0.4	"
Titan 6	050709164805	4161	-0.3	71.6	4	
Dione 6N	050711090646	83464	0.6	342,8	0.4	Imaging (nontargeted flyby)
Dione 7	050807101529	1005	-12.8	287	0.4	"
Titan 8	050907075350	4957	-0.4	287,6	().3	
Titan 9	0510140405S2	4752	1.7	70.9	0.3	"
Titan I 1	051212191717	1852	76,8	275.8	10.1	Increase inc. for Iapetus flyby
Titan 12	060113164803	2132	49.7	275.7	15.5	
Iapetus I 3	060218105149	931	-21.2	204.3	15.4	Iapetus imaging
Titan I 3	060302091341	1511	11.6	109.8	20.2	Occultations of Saturn, rings
Titan 16	060521024517	1125	-67.6	314.2	8.5	Reduce inc., rotate clockwise
Titan 17	060622000041	1740	-s?.,4	106	0.4	Rotate clockwise
Titan 18	060711185333	2229	0.9	250.5	0.4	
Rhea 19N	060821 045323	68841	1.3	297.4	0.4	Imaging (nontargeted flyby)
Titan 19	060823132837	1958	0	107.9	0.4	Rotate clockwise
Titan 20	060912081655	11924	0.7	66.5	0.4	
Enceladus 20N	060914034348	5421	I 0.4	20.5	().4	Imaging (nontargeted flyby)
Rhea 20N	060914154510	33970	-0.9	93.5	0.4	Imaging (nontargeted flyby)
Tethys 21	061004 161843	648	81.6	257.4	0.4	Rotate clockwise
Rhea 22N	061025102642	58934	-0.9	281.3	0.4	Imaging (nontargeted flyby)
Titan 22	061026184809	11308	-0.1	293.2	0.4	Rotate clockwise
Titan 23	061115133003	2224	0	251.1	0.4	
Titan 24	061228073112	1028	-1.1	108.3	0.1	Target to Enceladus
Enceladus 25	070116184529	605	-8.3	215.1	().2	Enceladus imaging
Enceladus 27N	070228093845	87264	0.2	267.3	0.2	imaging (nontargeted flyby)
Dione 27N	070228142407	76634	1	276.8	().2	imaging (nontargeted flyby)
Titan 27	070302035101	16784	4.4	292.2	0.4	Rotate clockwise
Titan 28	070321220139	2189	-0.4	251.4	0.4	
Dione 29N	070501 164026	24268	-0.5	347.4	0.4	I maging (nontargeted flyby)
Titan 29	070503154659	2027	-0.9	106,5	0.3	Rotate clockwise
Titan 30	070523102259	1 000	85.3	328.7	14.3	Occultations of Saturn, rings
Mimas 31N	070618054619	97383	-28	208	14.4	Imaging (nontargeted flyby)
Titan 32	070710062913	1050	59	241.3	2.3	Reduce inc.
Titan 33	070811 034147	2098	-11.4	68.7	0.3	Position node for hi-inc seq.
Enceladus 33N	070813020914	27267	2.3	251.6	0.3	I maging (nontargeted fl yby)
Enceladus 34N	070902052549	53700	-0.6	96.6	0.3	Imaging (nontargeted flyby)
Titan 35	070924143650	95(I	-52.9	120.3	14.2	Ill-inclination sequence..
Titan 36	071010133145	950	-76	174.8	29,7	(Saturn-ring occs @ hi inc.,
Titan 37	071026120707	950	.65.5	176.3	40,9	minimum alt. Titan flybys,
Dione 38N	O7I1O9O23259	99682	0.8	305.9	40.9	Titan occultations)
Titan 38	071111 103536	950	-26	140.8	51.5	"
Titan 43	080114 044801	950	-16.1	145.6	58.7	
Dione 45N	080201 180659	91316	5.4	36.3	58.7	Imaging (nontargeted flyby)
Tethys 46N	080212094843	3s9s7	-22.3	104	58.7	Imaging (nontargeted flyby)
Titan 46	080215014924	950	-17.5	157.9	64.7	I Ii-inclination sequence
Tethys 49N	080311 175916	33630	-12.8	178.4	64.7	I maging (nontargeted flyby)
Titan 51	080402 212911	1022	29.6	133	70.3	I 1]-inclination sequence
Titan 53	080418 194951	950	-19.9	177.2	72.1	"
Titan 54	080504181214	958	32.7	150.1	76	

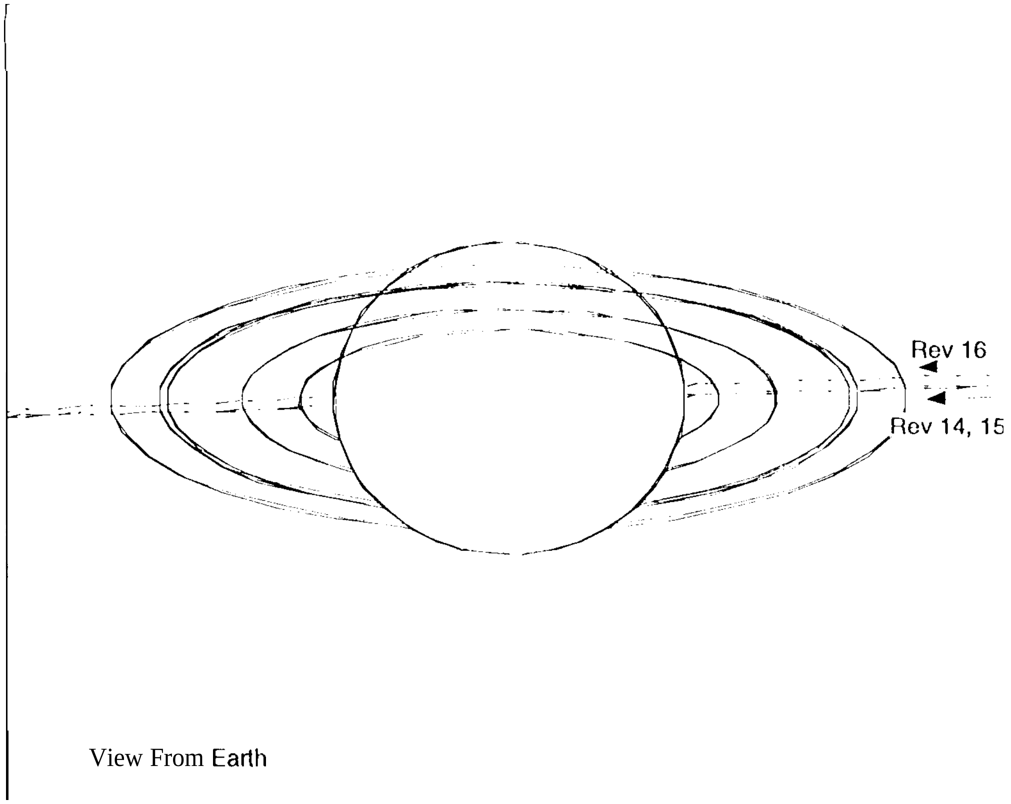


Fig. 6. Low-inclination Saturn/ring occultation sequence. The orbiter's trajectory is shown passing directly behind Saturn and the rings, at it appears to an Earth-based viewer. These passes occur in the sample tour after the Titan 13 flyby.

A long series of' flybys is then begun which rotates the orbit in the clockwise direction, toward the magnetotail. Alternating outbound/period-reducing and inbound/period-increasing flybys are used, in a mirror image of tile counter-clockwise rotating sequence at the beginning of the tour. A few interruptions of this sequence are allowed on the way 10 tile magnetotail to accomplish other science objectives, including a flyby of Tethys on orbit 21 and a flyby of Enceladus on orbit 25.

By orbit 30, the orbit orientation is such that an inbound Titan flyby aligns the line of nodes nearly normal to tile Earth line, yielding another opportunity to obtain occultations of Saturn at minimum inclination (as was done earlier using outbound flybys). The inclination required to achieve an occultation is less at this point in tile tour than earlier, because the declination of Earth with respect 10 Saturn's equator is less. The Titan 30 flyby is employed to take advantage of this opportunity, increasing tile inclination to achieve equatorial occultations of" Saturn and the rings on orbits 30 and 3]. Titan 32 anti Titan 33 lower the inclination to near the equator. Whenever tile orbital plane is inclined significantly 10 the equator, all flybys most take place at the same point in Titan's orbit; consequently, the Titan 30, 32, and 33 flybys are ail inbound.

Starting with Titan 35, the rest of the tour is devoted to a sequence of flybys designed 10 raise the inclination as high as possible (in this case, 76 deg.) Maximum inclination is desired for ring observations and in-situ field and particle measurements. For this sample tour, the orbits during the high-inclination flyby sequence are placed nearly opposite the sun, close to the magnetotail, in order to assure several Saturn occultations during the high-inclination sequence. Because the high-inclination sequence is time-consuming, it is desirable to begin it as early as possible. This sequence can be started sooner if the Titan flybys are outbound than if they are inbound. The Titan 33 flyby lowers the orbital plane to near the equator in order to be able to target 10 a subsequent outbound flyby (Titan 35), achieving tile desired nodal align ment at which to start the high-inclination sequence.

First orbit cranking, and then orbit pumping (after a moderate inclination has been achieved) are used to increase inclination, reducing the orbit period to 7.1 days in the process (that is, 9 orbiter revs for each Titan rev). The closest approach altitudes during this sequence are kept at the minimum allowed value in order 10 maximize gravitational assist at each flyby.

The inclination quickly exceeds the minimum value required to achieve occultations, after which occultations are achieved on ever-y orbit. When the inclination is much greater than the required minimum, the entry and exit points are nearer Saturn's pole regions than its equator. Views of some of the Saturn occultations obtained during the high-inclination sequence are illustrated in Figure 7 as they appear to an Earth-based observer. These occultations provide valuable information on Saturn's atmosphere. However, their entry and exit points are too far from the equator to allow passage behind the rings. in all, the sample tour contains 32 occultations of Earth by Saturn, 5 of which are near-equatorial; the remaining 27 occur during the high-inclination sequence.

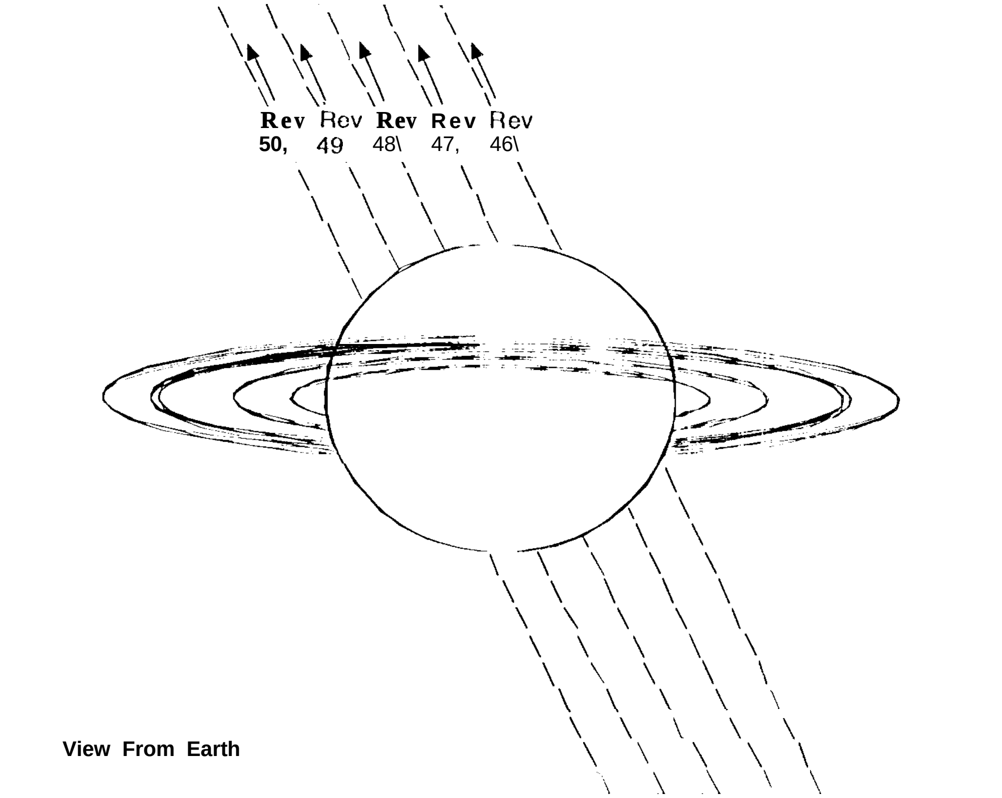


Fig. 7. I ligh-inclination Saturn/ring occultation sequence. The orbiter's trajectory is shown passing behind Saturn, as it appears to an Earth-based viewer. These passes occur in the sample tour after the Titan 46 flyby

Ten occultations of Earth by 'l'i(an occur during the sample tour, allowing probing of Titan's atmosphere. The 33 Titan flybys provide opportunities for radar coverage of various portions of Titan. Because of conflicting scientific requirements and orbiter operating constraints, radar swaths cannot be taken at every flyby. Similar flybys (for example, inbound/period-reducing flybys) have similar ground tracks.

The tour ends on 1 July, 2008, 4 years after insertion into orbit about Saturn, during orbit 63. The aimpoint at the last flyby, "l'i Ian 54, is chosen 10 target the orbiter to a subsequent Titan flyby to provide tbc opportunity to proceed with more flybys during an extended mission, if resources allow.

6. CONCI ,US1ONS

The Cassini mission can make use of a large experience base in tour design accumulated during the Galileo mission to Jupiter. However, differences between the Saturnian and Jovian environments and the scientific objectives of Cassini and Galileo necessitate development of new tour design techniques for Cassini. The sample tour presented here illustrates methods of designing Cassini tours which achieve the mission's scientific objectives while meeting mission-imposed constraints. Trade-offs identified during the course of designing this sample tour will be examined further in preparation for design of the final Cassini tour.

7. ACKNOWLEDGMENTS

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